Sectional Analysis of Cross-Laminated Timber Beams as a Design for Fire Methodology

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ABSTRACT

Current European structural fire design methodology for cross-laminated timber (CLT) elements predominantly uses a reduced cross-section method, which fails to realistically capture the variation of mechanical properties of timber at elevated temperature or with variable grain directions. A thermomechanical sectional analysis, compared against fire tests on CLT slab strips is presented herein, using two different sets of temperature-dependent mechanical properties available in the literature. This is investigated as an alternative, more rational design approach for CLT flexural elements exposed to fire. Initial results show reasonable correlation with experimentally observed failure times (i.e. fire resistances). Both failure time and deflection response are shown to depend on the temperature-dependent mechanical properties of timber used as modelling inputs, and the recommended properties presented in the Eurocode may not be suitable on the basis of the testing and analysis presented. Further research is needed to corroborate this conclusion.

INTRODUCTION & BACKGROUND

Cross-laminated timber (CLT) is one of several engineered timber products gaining popularity in the construction industry due to its attractive aesthetic, structural, and sustainability credentials. One significant factor preventing its widespread application in high-rise buildings is uncertainty around its performance in fire when used as the main structural frame. The majority of available research on timber's structural performance in fire focuses on determining the effective charring rates under standard fire testing furnace exposures, with consequent limited understanding of its behaviour in real fire scenarios. For the architectural aspirations of unprotected CLT structural members to be fully achieved, the fire behaviour and real structural response of CLT buildings in such scenarios must be properly understood.

CLT is formed from several lamellae of timber with adjacent lamellae arranged with perpendicular grain directions. This gives strength and stiffness in both directions, allowing CLT to be used as two-way spanning slabs, load-bearing and shear walls, and diaphragms. Existing structural fire design guidance for solid or glued laminated timber assumes axial/flexural strength in the grain direction only, and thus may be unsuitable for CLT elements. This paper examines an alternative method that accounts for the cross-wise laminations of CLT, and compares response predictions made using the more advanced analysis against experimental data from a recent set of flexural fire tests on softwood CLT beams.

EXISTING METHODOLOGY

The current design methodology recommended by Eurocode 5 [1] offers two approaches to determine the fire resistance of a solid or engineered timber element. The first of these is a 'reduced properties' method in which the residual section below the char line is analysed accounting for reduced overall mechanical properties, which are determined as functions of the element's heated perimeter and exposed area. This method is intended for beams, and is unsuitable for application to slabs [1]. The second method, which is the preferred method currently used in design is the 'reduced cross-section' method, in which a char layer is determined and is assumed to have zero strength, as is an additional "zero-strength layer" (typically 7mm) below the char, which is subtracted to account for the reduced mechanical properties of a certain depth (about 35-45mm) of heated timber below the char. This approach was originally developed by Schaffer et al. [2] using tests and modelling of glued-laminated beams tested in standard fire testing furnaces. Schaffer et al. [2] proposed that the reductions in mechanical properties over the (approximately) 40mm heated zone beneath the char layer could be accounted for by assuming that an additional 7.6mm of timber had zero-strength, with the remainder having full ambient strength. This method was not intended for application to CLT without further validation [3]. Due to the cross-wise layup of CLT, perpendicular lamellae have negligible strength. Thus, depending on the location of the char layer, the Eurocode's "zero-strength layer" could simply eliminate 7mm of strength from a weak lamella that contributes very little to the element's strength anyway, whilst neglecting the reduced mechanical properties of a heated strong layer underneath. This is illustrated in Figure 1 and is unconservative in terms of structural fire resistance predictions.

EXPERIMENTAL WORK

In order to verify (or otherwise) the existing approach and the more rational approach examined herein, CLT slab strips with a length of 2000mm, width of 300mm, and depth of 100mm were prepared with lay-ups of either of three or five lamellae of uniform thickness. In a series of ambient temperature control tests (performed in duplicate on each lay up) load was applied using a hydraulic actuator at 2mm/min in 4-point bending until failure. The 3-layer beams failed at an average load of 52.6±0.2kN by a 'rolling shear' failure mode, and the 5-layer beams failed at an average load of 40.4±2.3kN in a flexural (tension) mode.

Eight further tests (again in duplicate) were performed under sustained load and mid-span radiant heating, on samples loaded to 10 or 20% of their ultimate ambient strength found from the ambient temperature tests. Only the constant moment region of the beams was heated (from below) with a radiant panel; the remainder of the cross-section was insulated with mineral wool to promote one-dimensional heat transfer. The incident radiant heat flux was 25 to 30kW/m^2. These tests were intended to investigate the effects of loss of section on structural capacity and failure mode. The Eurocode's methods were initially used to predict the charring and residual cross-section, from which reductions in structural capacity during heating were predicted.

Whilst it was observed that failures were predicted reasonably accurately using the Eurocode approach, the observed charring rate from the tests did not agree well with those predicted by the Eurocode's notional charring rate of 0.65mm/min. Experimental charring rates of about 0.5mm/min were observed based on in-depth temperature measurements; these resulted in experimental char depths of only 20mm and 35mm at failure for the 3- and 5-lamellae samples at 20% loading respectively, rather than the 26mm and 49mm that would be expected on the basis of the Eurocode. This means that zero-strength layer depths of 13mm or 21mm would be required to corroborate the Eurocode's effective cross-section approach for the 3- and 5-lamellae samples respectively, thus clearly demonstrating the inadequacy of this approach, both for standard and non-standard heating regimes [4]. It was also noted that the charring was not perfectly one-dimensional; some charring occurred outside the heated region.

Predictive models developed to predict the beams' time-deflection response also showed that the zero-strength layer approach failed to capture the physics of the problem, and that the concept of a zero-strength layer applied to CLT is fundamentally flawed due in part to grain-dependent strength parameters [4]. The possibility of applying a thermomechanical sectional analysis approach is now being explored, in which temperature-dependent mechanical properties are mapped onto the known temperature profile within the heated CLT elements to give a physically based representation of the strength over the cross-section. Such a method has the additional advantage that it can be applied to any heating scenario where the temperatures are known or can be calculated.

SECTIONAL ANALYSIS METHODOLOGY

Analysis Approach

To account for the different orientations of lamellae present in CLT, a more rational sectional analysis method is proposed. CLT cross-sections are divided into elemental thicknesses of depth Δx. The temperature of each element is determined for each time step, based initially on experimental data obtained during testing in the current study [4]. Factors for reduction of elastic modulus with temperature, such as those in Eurocode 5 [1] are applied over the cross-section, and a new "transformed width" is determined for each elemental layer using Equation 1:

$$w_{eff,i} = E_i/E_0\, w \tag{1}$$

where $\boldsymbol{E_i}$ and $\boldsymbol{E_0}$ are the elastic moduli of each element and the original cross-section respectively (a similar method is typically used for ambient design of CLT, wherein a transformed cross-section is developed by reducing the effective widths of the perpendicular layers). An example of a transformed section during heating is shown in Figure 2, where both the weak and heated strong sections have been transformed.

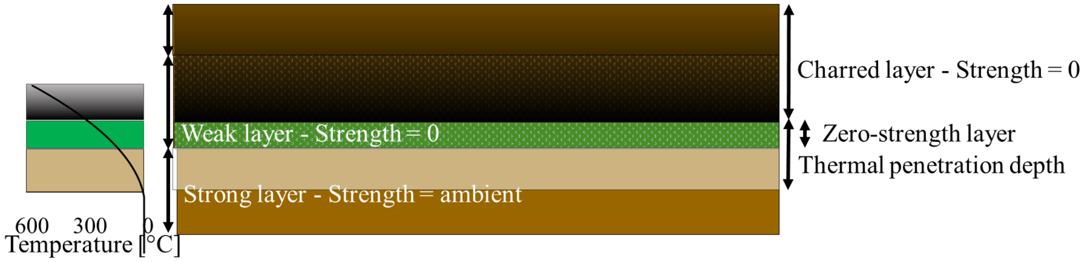

Figure 1: Charring of a CLT element highlighting strong and weak layers and extent of the heated region

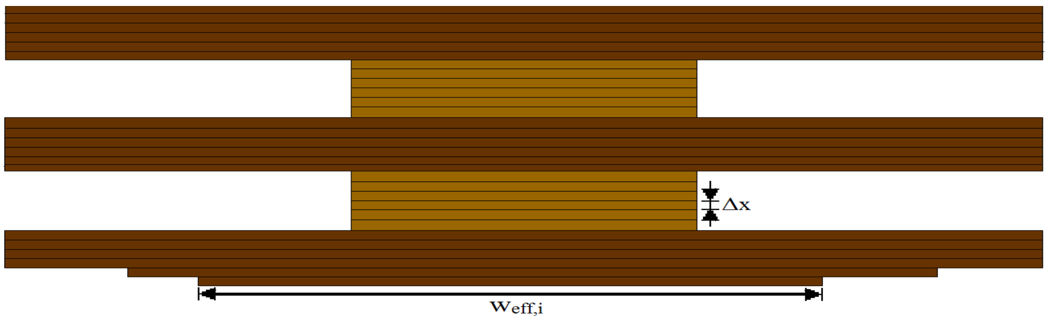

Figure 2: Transformed CLT cross-section showing element discretisation and effective widths

The elastic section modulus is then calculated using a MATLAB script, and the tensile stress in each of the fibres is calculated. This is compared against temperature-dependent tensile strengths, again calculated based on Eurocode 5 reduction factors (although for tensile strength in this case) and any elements in which stress exceeds strength are ignored. The elastic section modulus is then recalculated, and the elastic section modulus for failure (S_f) is given by Equation 2 [6]:

$$S_f/S_0 = P_a/P_f \tag{2}$$

where $\boldsymbol{P_a}$ and $\boldsymbol{P_f}$ are the sustained applied and ambient ultimate failure loads, respectively. It is noteworthy that the experimental thermal profiles used in the analysis were derived by fitting a polynomial curve to the in-depth temperatures measured in the tests [4], since a smooth thermal profile was needed to implement the analysis calculations described.

The beams' deflection responses can also be predicted from the transformed section and the applied load. This analysis requires the heated and unheated portions of the beams to be considered independently. The support conditions were assumed as pinned, with deflection and rotation continuity at the interface between the heated and unheated portions of the beam. Flexural stiffness matrices for both regions were then calculated, and the resulting mid-span deflection determined for each time step.

Material Input Parameters

A central consideration challenge in accurately predicting the in-depth flexural elastic modulus of the samples arises in determining the temperature-dependent mechanical properties for heated timber, both along and perpendicular to the grain direction. Figure 3 shows various data sets and proposals from the literature. Considerable variation in the data is evident.

The variation in elastic modulus with temperature proposed by König and Walleij [7] is based on bending tests [18] and are used by Eurocode 5. The König [18] samples were heated on one side only, and the strength and flexural stiffness reductions were back-calculated based on the observed element response. Since these are not direct measurements, the results are *effective* parameters specific to the test setup used, rather than directly measured material properties. Since the cross-section used by König [18] was significantly different (145mm deep x 45mm wide) to that used herein, the resulting mechanical properties may not be suitable. Indeed, Table I shows that use of the König and Walleij [7] results in consistent under-prediction of the fire resistance.

Other data sets in Figure 3 are based on tests under different conditions; e.g. the results from Östman [13], Young [11], and Schaffer [17] are all derived from small-scale tensile tests. Tests in pure tension, whilst giving actual properties rather than effective properties, may not be the most suitable for application to bending tests due to the differences in mechanical response in tensile and bending tests.

To investigate the effect(s) of the assumed variation in elastic modulus with temperature on the model predictions, the model was re-run using Thomas' [8] tensile elastic modulus data, with all elements at temperatures above 300°C assumed to have zero strength and stiffness. Thomas' model is based on the same principles as König and Walleij [7] and used the test results from König [18], but only calculated the elastic modulus at failure, whereas König and Walleij calculated the values at each instant in time throughout the tests based on the time-history of mid-span deflection, also using the results from König [18] supplemented with additional tests [7]. Whilst the two methods give similar results for the compressive elastic modulus, as shown in Figure 3, for tensile elastic modulus the methods give different results. As with König and Walleij's model, Thomas' model only gives *effective* parameters, and may not be appropriate for the current tests; however they are used herein for comparison and the results are given in Table I.

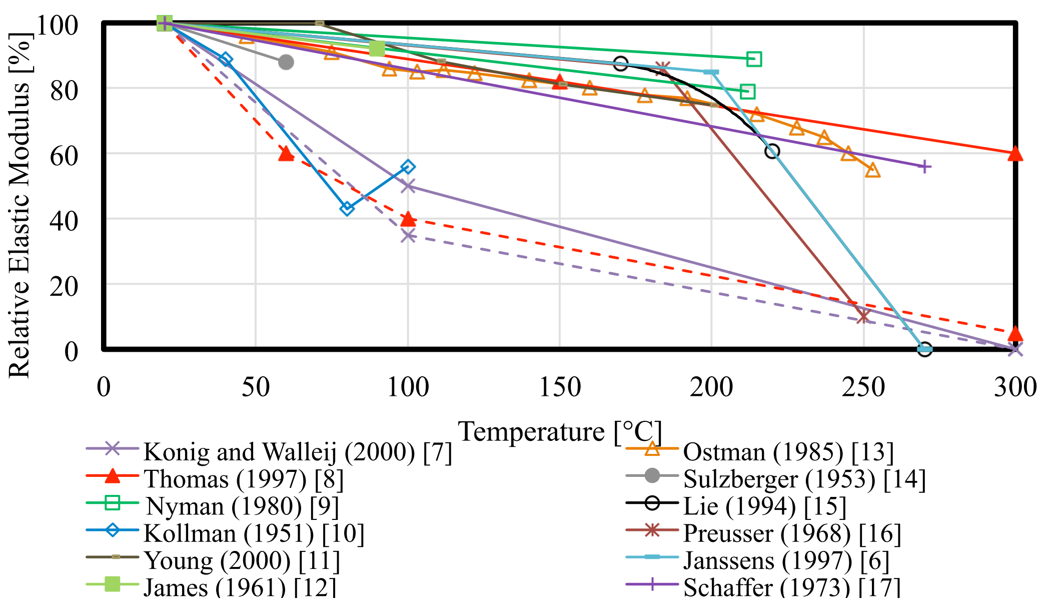

Figure 3: Elastic modulus of softwood timber, parallel to grain, as a function of temperature from the available literature; compressive elastic modulus is shown by dashed lines

RESULTS AND DISCUSSION

The observed and predicted failure times from each of the eight fire tests are given in Table I, where the clear underestimation of failure times by the model using Eurocode 5 property variation is clear. It is evident that, using property variations according to Thomas [8] gives better predictions for most tests, with an average prediction error of +6%, compared with +30% for the Eurocode 5 properties.

The first of the 5-lamellae tests, which failed after 86 minutes, was predicted not to fail using Thomas' properties; temperature measurements were taken up to 104 minutes, at which point the Thomas' properties model predicted a load-bearing capacity greater than the applied load of 10% of the ambient capacity. Examining the predicted and measured deflection responses for this test, shown in Figure 4, it can be seen that the response closely resembles the Eurocode model predictions. In some other tests, the deflection response more closely resembled the Thomas' model, whereas in others it did not show a particularly strong correlation to either model. Four typical time-deflection responses for different beams, along with their model predictions are shown in Figure 4.

The generally poor correlation is likely primarily due to incorrect mechanical property relationship parameters being used. Two sets of properties from opposite ends of the spectrum of available data in Figure 3 were selected and used to study their influences on the predictions. Figure 4 shows that the majority of experimental results lie somewhere in between these two models. It is therefore likely that the "true" variation of mechanical properties with increasing temperature lies somewhere in between these two extremes. Therefore, understanding and characterising suitable material properties for timber at elevated temperature is vital for implementation of this (and similar) model. Furthermore, due to some slight two-dimensional charring effects outside the heated zone in the tests presented herein, mechanical properties in the "non-heated" region would also be slightly reduced, resulting in an over-prediction of the beam's strength and stiffness using the proposed model.

TABLE I: MODEL-PREDICTED AND EXPERIMENTALLY OBSERVED FAILURE TIMES FOR CROSS-LAMINATED TIMBER BEAMS UNDER SUSTAINED LOAD DURING HEATING

Test	Sustained load/ ambient ult. load [%]	Actual failure [min]	Predicted failure (EC5 properties) [min]	Under-prediction (EC5 properties) [%]	Predicted failure (Thomas' properties) [min]	Under-prediction (Thomas' properties) [%]
3-lamellae						
1†	10	60*	58	3	67	-11
2†	10	89	54	39	60	32
3	20	38	29	23	42	-10
4	20	39	27	31	40	-3
5-lamellae						
5	10	86	69	20	None	n/a
6†	10	85	73	15	89	-5
7	20	74	32	57	42	43
8†	20	76	61	20	79	-4

*test erroneously halted prior to failure due to a sudden (but not catastrophic) deflection
†particularly poor fit to thermocouple data

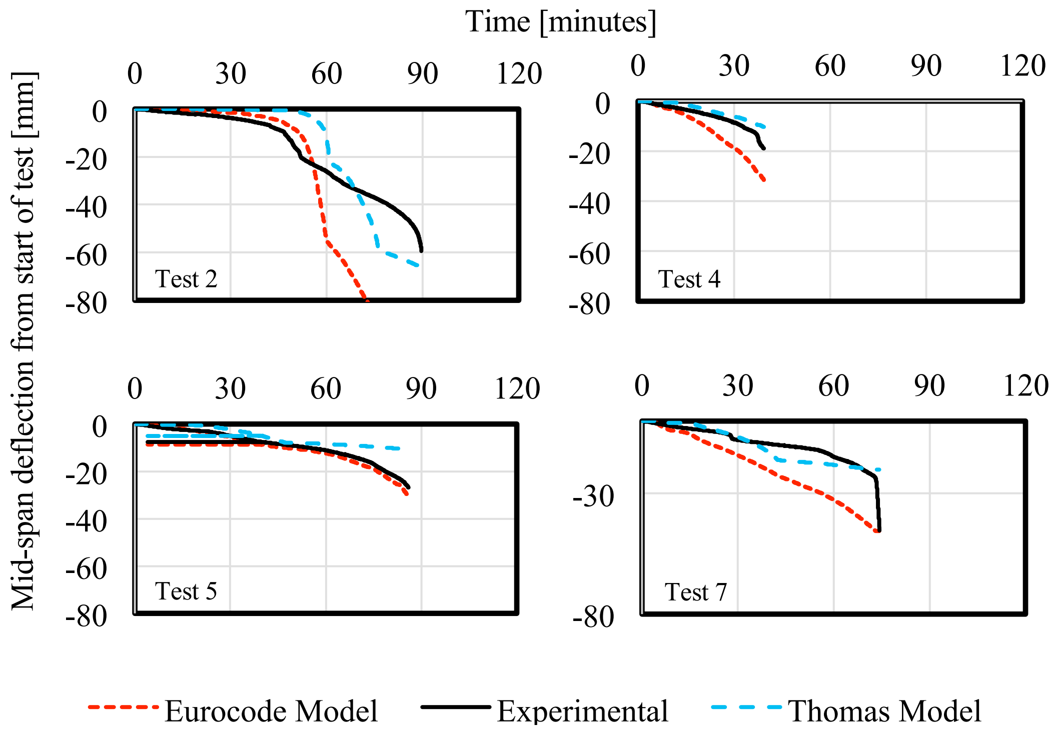

Figure 4: Predicted and experimental deflection responses for tests 2, 4, 5, and 7

CONCLUSIONS AND FURTHER WORK

A thermomechanical sectional analysis has been applied in an attempt to undertake a rational analysis to predict the structural response (i.e. deformation response and fire ressitance) of CLT flexural elements. The initial results show a reasonable ability to predict failure times (i.e. fire resistances) given a known (measured) time-history of internal temperature profiles.

For the majority of samples tested, Thomas' [8] properties provide a better estimate of failure time than the Eurocode 5 [1] suggested properties, with an average prediction error of 6% compared with 30%. The predicted deflection responses in Figure 4 show that both sets of properties give poor predictions of the response. It can be observed, however, that the predicted deflection response depends heavily on the assumed variation of mechanical properties of timber with temperature – it is therefore vital to better understand and obtain more realistic properties for various configurations and conditions of timber under elevated temperature exposures.

Once these material properties are known with confidence, they should be validated across multiple scales and structural and loading configurations, including beams, columns, and slabs to allow use for predicting CLT mechanical response during heating. Methods for predicting the temperature profiles in heated CLT, rather than using the experimental data or notional charring rates, should also be explored in future work, to allow a fully predictive model for CLT structural elements in fire. This will require a detailed heat transfer analysis, and depending on the orientation, one-dimensional heat transfer analysis may be insufficient.

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